Verification of the Performance of Future Energy Resources' *SilvaGas*® Biomass Gasifier -- Operating Experience in the Vermont Gasifier

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The Burlington, Vermont gasifier is the first commercial scale demonstration of Future Energy Resources ***SilvaGas***® biomass gasification process. The gasification plant is the largest operation of its type in the United States. The Burlington plant is coupled to the McNeil station of the Burlington Electric Department and is being used to evaluate and demonstrate the gasification technology both as a producer of fuel gas and in a combined cycle with a gas turbine power generation system. The *SilvaGas* process was the first process to integrate a biomass gasifier with a gas turbine during pilot operations at Battelle's Columbus, OH facilities.

This paper describes the *SilvaGas* process and its potential application for fuel, power and chemical synthesis applications. In addition, operating results from the Vermont gasifier including gasifier performance, plant operability, and flexibility are discussed. Operation of the *SilvaGas* demonstration plant has verified that the process is very stable, can utilize feedstocks with moisture contents ranging from 10 to 50+%, produces a gas composition with a heating value of 11-14 MJ/Nm^3 (450 to 500 Btu/scf), and has high conversion efficiencies. The continued activities at the Vermont gasifier site and their impact on process improvements are also discussed.

The plant operation has helped to validate the technology and provide a sound basis for discussions leading to the establishment of commercial projects around the world. Future Energy is in the process of developing a number of commercial projects based on the process the status of which will also be discussed.

INTRODUCTION

Recent price increases for various forms of energy along with projected shortages of supply have resulted in renewed interest in alternative fuels. These situations, combined with a desire to provide sustainable energy supplies with minimal environmental impact have resulted in increased emphasis on biomass as an energy source. In order to have the widest application today, however, fuels derived from biomass must be interchangeable with conventional fossil fuels.

Future Energy Resources (FERCO) has been developing a biomass gasification process that achieves this goal. The ***SilvaGas®*** gasification process provides a means to convert a range of solid biomass fuels into a medium calorific value gas that can be directly substituted for natural gas or as an input for chemical synthesis applications. For gas turbine power applications, the use of biomass fuels provides a means to achieve high overall power generation efficiencies without introducing additional greenhouse gases to the environment. By converting the biomass into this high energy density gaseous fuel, significantly higher power generation efficiencies can be achieved relative to direct combustion based systems (approximately 40% power generation efficiency compared to a maximum of 25% with conventional biomass systems (HHV basis)).

Transforming solid fuels such as coal or biomass into gas so that these higher efficiencies in combined cycle systems can be achieved is a goal of the United States Department of Energy (DOE) and the European Union.

Process Background

The Future Energy Resources Corporation (FERCO's) *SilvaGas* biomass gasification process was developed to convert biomass into such a gaseous fuel. Unlike other biomass gasification processes, the FERCO process is not based on starved air combustion, but rather rapidly heats raw biomass in an air free environment to minimize tar formation and create a solid residue char that is used as a heat source for the biomass heating. Significantly less emissions are produced in the process because of the relative ease of treating the high energy density, medium heating value gaseous product.

The process is specifically designed to take advantage of the unique properties of biomass, such as high reactivity, low ash, low sulfur, and high volatile matter. The reactivity of biomass is such that throughputs in excess of 14,600 kg/hr-m^2 (3000 lb/hr-ft^2) can be achieved. In other gasification systems throughput is generally limited to less than 500 kg/hr-m^2 (100 lb/hr-ft^2). Other competing biomass gasification processes were either developed originally for coal gasification or were heavily influenced by coal gasification technology and therefore do not take full advantage of the properties of biomass.

The *SilvaGas®* Process

The *SilvaGas* gasification technology underwent initial development at Battelle's Columbus Laboratories as a part of the DOE's Biomass Power Program. In the process, biomass is indirectly

heated using a hot sand stream to produce a medium calorific value gas (approximately 17 to 19 /Nm^3 as is shown schematically in figure 1.

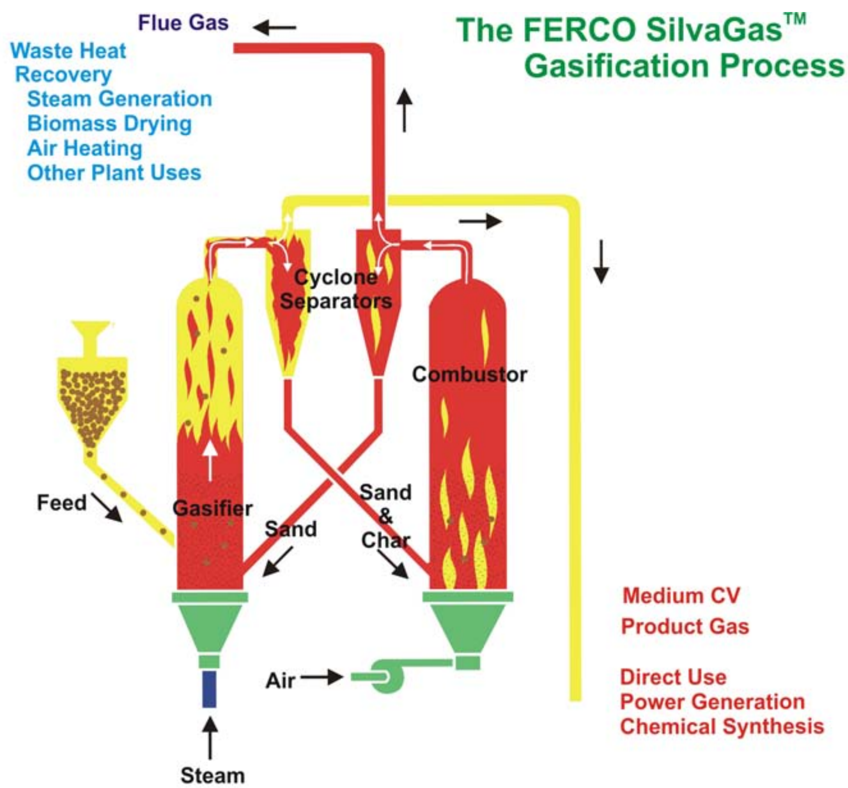

Figure 1. The *SilvaGas*® Gasification Process

The process uses two circulating fluidized bed reactors as the primary process vessels. The circulating sand is used as a heat transfer medium to rapidly heat the incoming biomass and convey char from the gasification reactor into the process combustor.

Thermal gasification of biomass provides flexibility for the production of the complete slate of products in a virtual "biomass refinery". Indirect gasification holds great potential as a means for generating a flexible product gas capable of fulfilling a range of energy needs by its direct use or as input to a synthesis reactor. By providing a full scale demonstration of the *SilvaGas* process, the VGP has been used to validate the technology and confirm its commercial viability. The flexibility of the medium Btu gas produced in the *SilvaGas* process allows its use for:

- Direct use as a fuel gas that can be interchanged with natural gas or distillate oil
- Co-fired with biomass or fossil fuels for heating or power applications,
- Use as a fuel for advanced power generation cycles including turbines or fuel cells, and
- Use as a feed gas for synthesis applications such as production of Fisher Tropsch liquids, alcohols, and hydrogen.

TECHNOLOGY STATUS

The process has been under development since the late 1970's and has been extensively tested with woody biomass, herbaceous crops (switch grass), a prepared RDF from municipal wastes, and a variety of other waste biomass fuels. Testing in the 10 ton per day Process Research Unit (PRU), has coupled a Solar Spartan gas turbine (200 kW) power generation system to the PRU gasifier. This testing demonstrated the feasibility of biomass gasification for power generation, and has provided valuable design data for commercial scale process applications.

A Commercial Scale Demonstration Plant

After over 20,000 hours of operation in the PRU, a commercial scale demonstration plant based on the *SilvaGas* process was constructed in Burlington, Vermont. Burlington Electric Department's (BED) McNeil station was selected as the site for this demonstration plant. BED has a long history with biomass based power generation. The McNeil station, at 50 MW, is one of the world's largest wood fired power stations. The McNeil station uses conventional biomass combustion technology, a stoker grate, conventional steam power cycle, and particulate removal using ESP's. BED hopes to improve its generating efficiency by implementing a gasification combined cycle system.

The commercial scale demonstration of the *SilvaGas* process underway at the McNeil Generating station in Burlington, Vermont was designed for 182 dry tonnes (200 tons) per day of biomass feed. The gas produced is being used as a co-fired fuel in the existing McNeil power boilers. In subsequent phases of the program, a gas combustion turbine is planned to be installed to accept the product gas from the gasifier and confirm the results from the PRU testing.

The program has been conducted in three phases, (1) design, (2) construction and initial operation firing the product gas in the McNeil boiler, and (3) additional gas cleanup, gas compression, and operation of a gas turbine power generation system.

Development Partners

The partners in the development of the process at the McNeil site are FERCO, Burlington Electric, Battelle, the US DOE, and the National Renewable Energy Laboratory (NREL). Battelle engineers invented the process and conducted the initial developments under contract to the US DOE in the early 1980's. In 1992, FERCO purchased the rights to the technology from Battelle and is now the owner of the worldwide rights. In 1999, FERCO was reorganized and refinanced, bringing in additional shareholders including the Turner foundation. FERCO is developing renewable energy projects based on the gasification technology worldwide. These projects will build on the operations at Burlington.

The US DOE and NREL provide valuable technical support to the program along with program management.

PROGRAM GOALS AND OBJECTIVES

The development program at McNeil has as its primary objective the demonstration, at commercial scale, of the *SilvaGas* gasification process and associated support technologies. These technical goals parallel the Department of Energy's goals for bioenergy and the progress made by the Vermont Gasification project establishes its role as a key element for future development of biomass derived products. Thermal gasification of biomass provides flexibility for the production of a complete slate of products as described above in a virtual "biomass refinery".

The scale selected is sufficiently large so that commercial scale process equipment could be utilized to eliminate so called "pilot plant compromises" in the design. The design of the plant includes all key process systems, with the exception of heat recovery.

The first operation of the Vermont gasifier in full steam gasification occurred in August of 1999. During the startup period, numerous design and operational changes to the plant were necessary to improve the performance of process auxiliary systems. No problems with the core process were encountered throughout the startup period, but a number of improvements to process auxiliary systems have been made these include materials handling, solids separation, and product gas scrubbing.

Figure 2. The Vermont Gasification Plant

Testing of the process and additional plant modification continued in early 2000. Continuous around-the-clock operation at the plant was achieved in August of 2000. Testing in the Vermont gasifier has produced positive operating results consistent with those previously achieved in the PRU including measurements of gas composition, gas production, feedstock flexibility, and gas conditioning and cleanup. As is the case with all development scale projects, some minor equipment modifications continue at the Burlington site.

OPERATING RESULTS IN THE VERMONT GASIFIER

Immediately following the initial around-the-clock test period, a series of "parametric" tests was undertaken to evaluate key process parameters such as wood feed rate, effect of wood moisture content, effect of wood particle density, and effect of combustor excess air. In addition, these tests allow for the performance of the system to be monitored over extended around-the-clock operating periods. At the conclusion of each of the parametric testing periods as well as the initial "24-hour" test, the unit was shut down in a controlled manner according to the prescribed operating procedures. Tests were concluded when the specific feedstock(s) for that test campaign were exhausted. The Vermont gasifier is a demonstration facility and, as such, is only operated for specific experimental campaigns, rather than in a "production mode".

The extensive data base developed in the PRU provided a sound basis for the design of the VGP system. This data base also provides a means to accurately measure the performance of the process at commercial scale. The primary process measurements used for comparison were gas composition, tar production, gasifier throughput, and carbon conversion to gas. In each of these measured parameters, the Vermont gasifier provided results equal to or greater than those generated in the PRU. These results showed that:

- Process stability has been demonstrated by around-the-clock operational periods utilizing wood feedstocks with moisture contents ranging from 10 to 50+%.

- Gas composition and production rates are identical with those projected based on pilot plant testing. Stable gas heating value of 450 to 500 Btu/scf has been demonstrated for extended operating periods. The product gas heating value has been shown to be constant regardless of changes in feedstock moisture.

- Gasifier throughput has been demonstrated to be over 150% of design corresponding to over 500 tons per day (350 dry tons per day equivalent) in the 200 dry ton per day "design" facility. The ability to process such a significantly larger amount of biomass further improves process economics and provides process flexibility for commercial applications.

- The system was able to be restarted within 30 to 45 minutes after plant shutdowns, demonstrating the ability of the process to provide for operational flexibility.

- Rapid response to feed rate changes demonstrated during operation
- Smooth operation of process observed with little operator attention required
- One operator per shift required (exclusive of feedstock handling)

Product gas composition

Biomass feedstocks, including wood are heterogeneous materials. Inherent moisture contents can range from near 0% to over 50% depending on environmental, harvesting and storage conditions. In any biomass gasification system, the moisture content of the biomass feed is important. With partial combustion based gasification systems, biomass moisture affects the product gas quality because more energy must be supplied to the gasifier to evaporate increased moisture in the feedstock thereby increasing carbon dioxide content of the produced gas increase with fuel moisture. Likewise, carbon monoxide decreases changing the heating value, mean molecular weight, and flame speed, as well as affecting the overall gasification efficiency. With the *SilvaGas* process, the increased energy requirement is provided by the circulating sand phase so gas composition remains unchanged. The process efficiency drops as a result of supplying this additional heat, but system response is sufficiently rapid to allow the adjustment of incoming biomass feed rate to compensate for the smaller quantity of product gas produced.

Gas composition of the gas produced in the process has been measured and found to be identical (on a dry, inert-gas free basis) with that measured in the PRU. Product gas heating value remains stable regardless of changes in feedstock type, ash content, or moisture content. This characteristic of the process had previously been demonstrated during pilot operation at Battelle and has been verified through the current testing program in Vermont. The validation of this characteristic of the product gas is quite important in the overall commercialization of the process, because it provides the ability of the *SilvaGas* process to be adapted to natural gas fired equipment without modification to controls or burner designs

Table 1 illustrates the composition of the product gas generated in the PRU compared to the gas currently being generated in the McNeil gasifier. The verification of the gas composition at commercial scale makes possible the commercial application of the *SilvaGas* process as a direct substitute for natural gas in direct-fired or gas turbine applications.

One obvious way of maximizing overall process efficiency is to utilize process waste heat in the process flue gas to dry the incoming biomass feed. Depending on site specific conditions and requirements, this waste heat can alternatively be used to heat air, raise steam, or for other process heating applications.

Figures 3 and 4 illustrate the consistency of the gas as well as the reproducibility of operation in the Vermont plant. The figures show 24 hour operating periods in the 2000 testing campaign and again in 2001, during which the feedstock moisture content varied from 10 to as high as 50%.

Reproducibility

Economical commercial operation depends on the ability of the process to operate with predictable response. Such predictability also allows for a high degree of automation to be applied to plant operations, reducing operating costs.

The testing campaigns in the Burlington plant have been designed to utilize a single set of process conditions as a "baseline". A specific set of conditions is established during each test campaign athat are duplicated at the beginning and end of each test period. During each of the baseline periods, gasifier performance has been remarkably reproducible.

Table 1. Product Gas Composition Comparison

Constituent	Pilot Plant Volume %	Demonstration Plant Volume %
Hydrogen	17.5	22.0
Carbon Monoxide	50.0	44.4
Carbon Dioxide	9.4	12.2
Methane	15.5	15.6
Ethylene	6.0	5.1
Ethane	1.1	0.7
Higher Heating Value	499 Btu/scf	468 Btu/scf

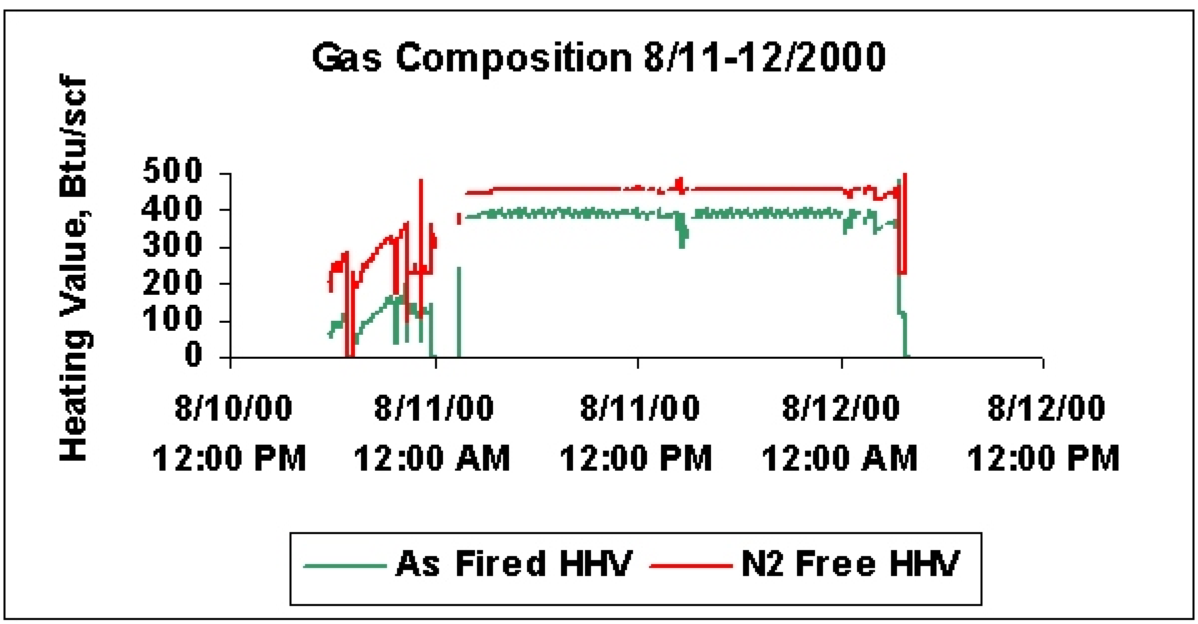

Figure 3. Gas Composition VGP Operation August 2000

Conversion of Incoming Biomass to Product Gas

Figure 5 illustrates the "carbon conversion to gas" performance for the Vermont gasifier compared to the data base developed for the pilot plant. The temperature range shown is that typical for most biomass feedstocks, including wood and municipal waste. As indicated, the curve can be extrapolated linearly if unusually dry (less than 10 percent) feedstocks are available or if additional energy is supplied to the process through heat recovery or additional fuel to the process combustor.

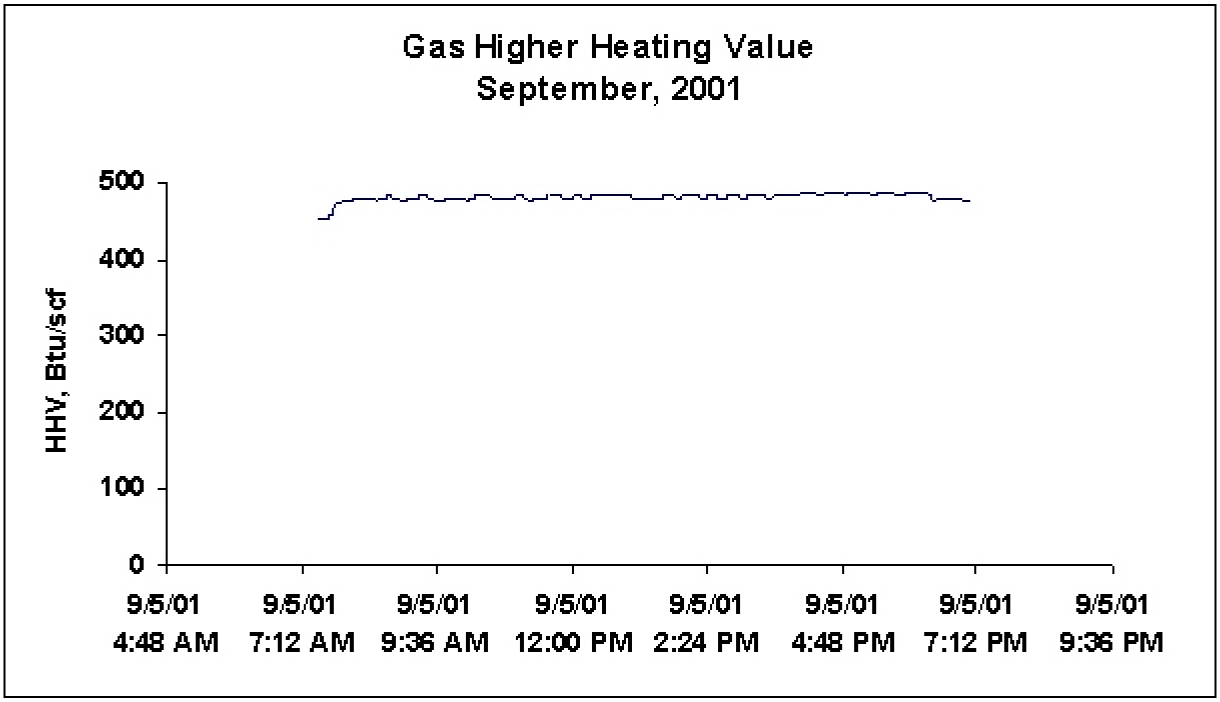

Figure 4. Gas Composition VGP September 2001

In no case was the performance measured in the Burlington plant lower than the pilot plant experience providing a sound basis for commercial plant designs based on the total body of data available (pilot plant plus demonstration scale plant). As is seen in figure 5, much of the testing in the Vermont plant has been at a somewhat lower temperature than the tests in the PRU due to higher heat losses in the Vermont gasifier. The refractory linings in the Vermont gasifier were chosen based on their ability to withstand the frequent startup and shutdown cycles typical in a demonstration facility rather than to optimize system heat losses. Improved heat loss characteristics will be specified for the refractory linings in commercial scale facilities.

System Response

The *SilvaGas* process uses short residence time circulating fluidized bed reactors for both the gasification and combustion systems. Testing in the Burlington gasifier has demonstrated the ability of these reactors to rapidly respond to process changes or upsets.

Changes in wood moisture are well tolerated by the process. During the testing program, as feedstock moisture levels were changed from level to another, the gasifier and combustor reactors responded within minutes to the changes. When large changes in moisture content were made rapidly (20 to 30% by volume), gasifier and combustor temperatures change more significantly so that a final steady state temperature, at each condition, were slightly delayed (about 1 to 2 hours depending on the magnitude of the moisture change) due to response of the system refractory. Even though the final steady state condition required some time to be reached, the gas production rate adjusted within minutes to within +/- 5% of the final equilibrium value.

Likewise, incoming wood feed rates can be changed as rapidly as required to match load requirements. The rapid system response to changes in system inputs allows the process to operate with a relatively wide turndown capability. The limitation on feed rate change is determined by feed system capabilities, not the gasification process. Additionally, the throughput of the vessels has an impact on overall process economics. Tests were run to evaluate the maximum throughput of wood to the plant. These tests showed that wood feed rates of over 350 dry tons per day could be achieved with no degradation in system performance. The results indicate that plant turndown capability is at least 1.5 to 1. Higher feed rates were limited by the capacity of the feed system in the plant.

At the Vermont site, both the product and flue gas from the gasification plant are used in the McNeil boiler. As a result, whenever the McNeil boiler operation is interrupted, the gasifier operation must

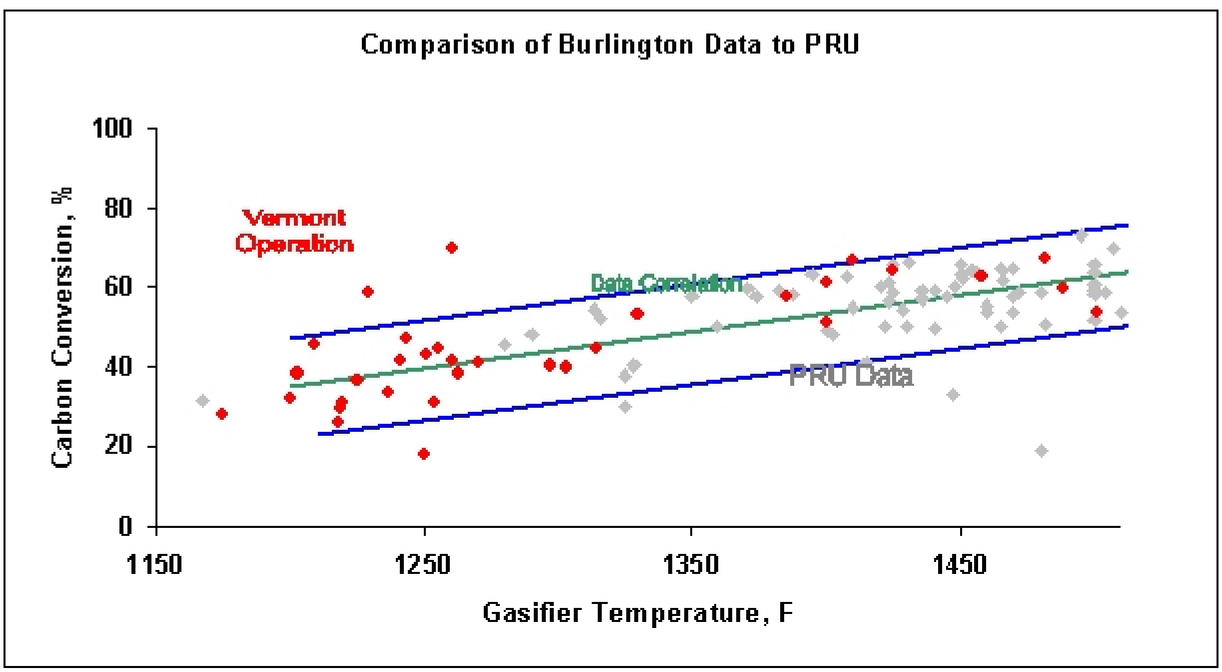

Figure 5. Comparison of Carbon Conversion to Gas Results

be halted until the boiler is back in service. These interruptions have occurred several times during the current testing program. By encountering such process upsets, we have shown that the entire gasification plant can be restarted within 30 to 45 minutes after an unexpected plant shutdown.

Gas Cleanup

While there are a number of routes by which biomass can produce an acceptable combustion turbine fuel gas, the critical stage in the process is treatment of the gas to remove impurities. Established methods, used for many years in the gas making industry, use wet scrubbing methods that can remove solid particles, soluble gases, soluble salts, and condensable liquids, to produce high levels of fuel purity. Their disadvantages relate to disposal of contaminated water and the associated heat losses. Overall, wet gas treatments present fewer problems to the turbine, but carry an efficiency penalty.

In a further development of the *SilvaGas* process, a novel hot-gas conditioning catalyst (DN34) has been developed that converts condensable products (tars) to lower molecular weight, and therefore, essentially noncondensable forms. This catalyst then allows for a much reduced loading on any scrubbing operation due to the elimination of the higher molecular weight materials.
A slip stream system was installed in the Vermont gasifier to further evaluate the DN34 catalyst performance at commercial scale. Test data generated during operation of the DN34 catalyst system indicated that up to 90% of the "tar" produced in the gasifier is destroyed in the catalyst at operating temperatures in the range of 1500 °F. This result is consistent with prior tests conducted on the PRU These results are illustrated in Figure 6.

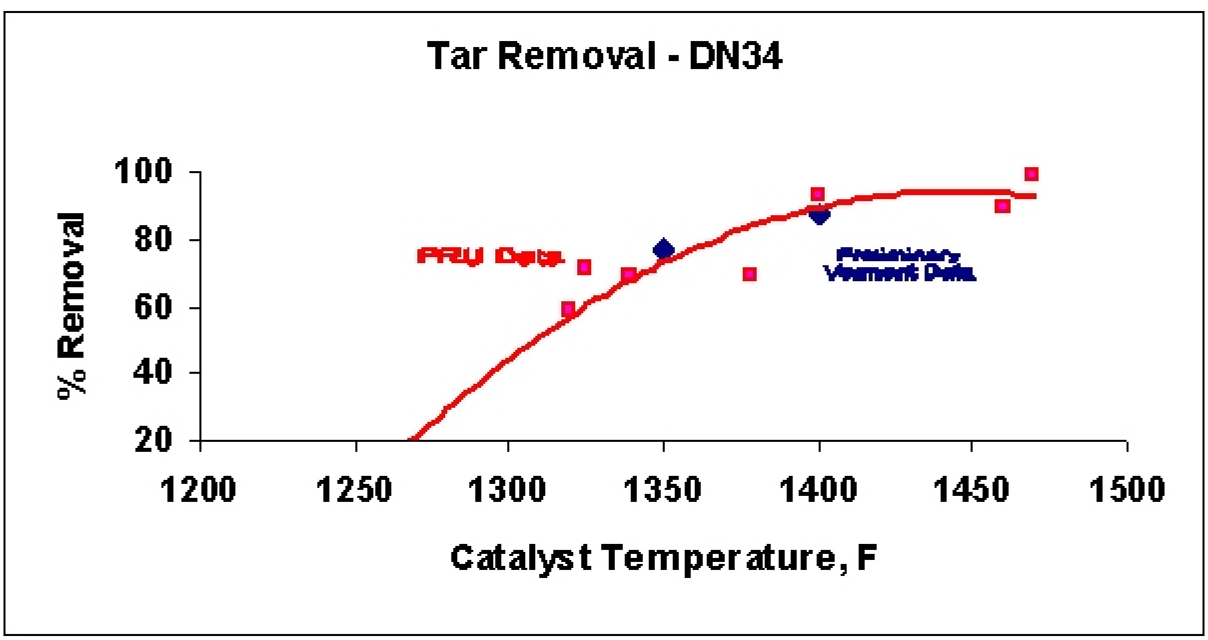

Figure 6. Tar Removal Results in the Vermont Gasifier

COMMERCIALIZATION ACTIVITIES

FERCO is actively pursuing additional commercial applications of the *SilvaGas* technology. These efforts have resulted in the signing of two commercial project development agreements (JDA's). One project with a major paper producer will gasify paper mill wastes to produce a gas for substitution in the mill's lime kiln and other natural gas users. The second will gasify wood waste and use the gas for direct fuel uses or power generation. In addition, a number of other projects are in negotiation and JDA's are expected to be signed in the near future. FERCO's project partners include several major U.S. utilities, Jacobs Engineering, and several international industrial concerns.

A variety of feedstock opportunities are being investigated for these projects. A significant number will use prepared MSW as the feed to the gasifier and provide the resulting product gas to existing landfill gas pipelines, thus augmenting the landfill gas supply. Other projects will use waste biomass resources from municipal or agricultural sources and generate gas that will be used as input to utility or industrial boilers as a co-fired fuel much as is being done in Vermont.

In each case the projected economics of these projects is favorable providing reasonable returns to the project investors. In general, these favorable returns can be realized without the need for financial incentives such as tax credits or capital subsidies.

PROJECTED PROCESS ECONOMICS

Based on the measured operating performance of the Vermont gasifier an estimate of the projected process economics for the *SilvaGas* process was developed. As discussed above, installations of the FERCO gasifier will be both for power and for production of a direct fuel replacement for natural gas.

Natural Gas Replacement

Capital costs were estimated based on a baseline process design by Jacobs Engineering, FERCO's engineering partner. Costs reflect a "brown field" installation at an existing industrial site, typical of most of the projects under development. Gasifier capital costs for a 400 ton per day (dry biomass basis) gasification plant have been estimated to be approximately $12 million.

This facility will produce slightly more than 200 million Btu/hr of medium Btu product gas plus recoverable sensible energy from the flue gas and product gas streams of approximately 46 million Btu/hr. The flexibility of the *SilvaGas* process allows for a range of biomass fuel to be utilized, thus providing the capability for the mixing waste and purchased biomass sources. If a net zero cost biomass fuel is assumed, a 12% ROI can be realized with a medium Btu gas selling price of $3.00 /MM Btu – a value competitive in today's energy market. These favorable economics reflect the simplicity of operation of the *SilvaGas* system. Only one operator is required for plant operations, exclusive of feedstock handling. It should also be noted that this gas selling price does not reflect any potential tax credits or "green energy" credits.

IGCC System

By coupling the *SilvaGas* gasifier to a gas turbine combined cycle, economical power production from biomass sources can be realized. An overall capital cost of $1270 per installed kilowatt of power has been estimated for such a system based on a 400 ton per day gasifier. Of this figure, $530/kW is for the gasifier island and $740/kW for the turbine system. Gasifier capital cost is slightly higher in the IGCC case due to gas cleanup and compression requirements.

A power generation efficiency of approximately 40% for the IGCC system (36% net efficiency) allows a project ROI of 15% with a power selling price of less than 5¢ / kWh. As in the natural gas replacement case, no tax or other incentives have been included in the power production costs.

CONCLUSIONS

Operation at the McNeil site has validated the performance of the *SilvaGas* gasification process. These development efforts have enabled the commercialization of the *SilvaGas* process to proceed at a rapid rate resulting in a number of potential projects. The performance of the system during testing in the Vermont gasifier has shown that:

- A medium heating value product gas can be produced from biomass at high conversion efficiencies without the use of pure oxygen providing a wide range of potential applications of the technology.
- High biomass throughputs can be achieved in compact reactors resulting in favorable process economics
- No extensive preparation of the biomass feedstocks is necessary for the process expanding the range of biomass materials that can be used in the process.
- The process can be applied commercially providing an economical alternative to conventional energy supplies

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